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Improvement of floor impact sound on modular housing for sustainable building

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ABSTRACT

The conjecture of “sustainable development” in construction is to prepare for good environmental conditions for the future generation. To do this, the reduction of wastes from construction and demolition processes is important to reduce environmental load in the area of construction.

The aim of this study is to approach methods to reduce construction wastes for development in a regulation perspective, and the suggested regulation for this is prefabricated construction regulation to reduce construction wastes from sites.

The majority of Koreans live in multi-unit dwellings, so in order to introduce modular regulation, the National Housing Act of Korea must be met. Therefore this study suggests a floor structure that is able to be applied to the modular construction method, as well as to satisfy the performance criteria of Housing Act (lightweight impact sound: 58 dB or less, heavyweight impact sound: 50 dB or less) in Korea. Experiments using a mock-up in addition to a simulation were performed to find structural vibration and sound pressure levels, followed by floor impact sources of the proposed floor structure.

As a result, floor impact sound was reduced on the floor structures of the same thickness comprised of different component materials, including a slab. Also, It was found that the amplification phenomenon of impact sound level by a bang machine was lower in the dry method compared to the wet method.

Contents

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1. Introduction

1.1. Background

“Sustainable development” was defined as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [1] in Our Common Future published in the Bruntland Report in 1987. The UK Government′s Sustainable Development Strategy defined this as all people throughout the world to satisfy their basic needs and enjoy a better quality of life, without compromising the quality of life of future generations [2].

In addition, recently energy efficiency and reducing carbon dioxide emissions of residential building is the main research subject because buildings have taken a total of national energy consumption of more than 23% and it has holds approximately 48.6% of construction orders.

Therefore the international agenda of low-energy and eco-friendly buildings has been adopt by International Energy Agency (IEA).

The conjecture of “sustainable development” in construction is to prepare for good environmental conditions for the future generation. To do this, the reduction of wastes from construction and demolition processes is important to reduce environmental load in the area of construction [3,4].

Construction wastes refer to wastes that are created during the construction process to the demolition, and generally consist of concrete, rubber, plaster, asphalt, blocks and complex chemical materials. Such construction wastes account for approximately 10–30% of all wastes [5].

In actual fact, there is approximately 200–300 million tons of construction wastes being produced in the U.S. alone [6], and those from Chicago accounted for 60.71% of all wastes produced in 2007 [7].

The proportion of construction wastes in all wastes is approximately 50% in the UK [8], and 37.08% in 2005 in Hong Kong [9].

To address the above problem there is active research into the reduction of construction wastes and recycling of such wastes [10]. It is important to approach this issue from the regulation perspective, as well as from material methods [11].

Modular construction has its strength which makes it possible to reduce construction error significantly which occur due to typical construction more than 50% of processes in modular unit construction method are manufactured in plant. In addition, as this construction method produces unit modular in factory at the time of foundation work and then assembles them, this method makes it possible to shorten approximately 50% compared with typical construction [12,13].

With this strength, modular construction has used primarily for military barracks in Korea. As domestic House Acts do not affect this low height and small buildings, there was no need to review criteria to block transferring sound in air and floor impact sound. However, certification for sound performance suggested by House Acts is necessary in order to activate apartment houses built by modular construction. However, since there is no building, which is constructed by modular construction in domestic area, it is necessary to develop floor structure satisfying performance criteria and research the developed floor impact sound characteristics.

1.2. Objective

Objective of this study build a base diffusion of residential buildings using modular construction and suggest improvement of floor structure reducing impact sound in residential buildings using modular construction.

Weight impact sounds generally occur in multi-unit dwellings and are often caused by young children running or jumping. Such sounds are irregular noise that is unpleasant for the person living in the floor below [14]. Heavyweight impact sounds are generally more unpleasant compared to lightweight impact sounds, and is the cause of low frequency noise under 100 Hz [15,16].

Methods to enhance heavyweight impact sound reducing performance among floor impact sound reducing performance criterion suggested by House Acts include [17] use of resilient material [18], increase of concrete slab thickness [19,20], change of floor structure [21,22] and increase of concrete strength [23,24].

An effective method to reduce low frequency noise under 100 Hz is to increase the slab thickness and weight [25–32].

By summarizing these results from above methods, shifting resonance frequency in floor structure in apartment houses to high frequency bandwidth is shown to be most effective [33,34]

Although most of previous researches are focused on impact vibration of apartment houses with RC structure, emitting noise and their evaluations through simulation and Mock-up experiment, impact vibration and emitting noise for floor structure from apartment houses constructed by unit modular method with lightweight steel frame is insufficient.

Therefore, this study is intended to investigate characteristics of vibration in floor structure and floor impact sound, which are applicable for apartment houses with domestic modular manufacturer′s common structure.

2. Overview of modular construction

2.1. Definition of modular construction

Modular construction is an architectural system whose fundamental technologies are developed from USA and Europe and this method is a production and construction method for buildings in a way that combines each box-type module produced from factory and laminates

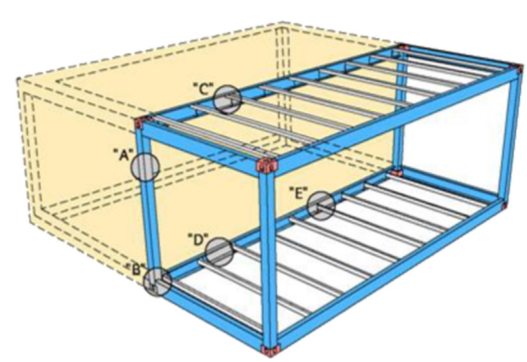

Fig. 1. Shape of modular construction method.

them [35–37]. When it comes to construction, this method makes it possible to shorten construction period by minimizing works on site and enhance the construction quality based on as much of factory production as possible [38–44]. Therefore, this method makes it possible to enhance production efficient by making parts from major structural subsidiary materials and it is also pursue wet construction method as it minimizes on-site construction by enhancing ratio of factory production. Therefore, modular construction can be figured to minimize construction period on site.

In general, shapes and characteristics of modular constructions are shown as Fig. 1.

2.2. Production processes

In general, more than 70% of construction processes in modular construction method such as structure, wall and equipments are produced in factory through standardized design drawing while

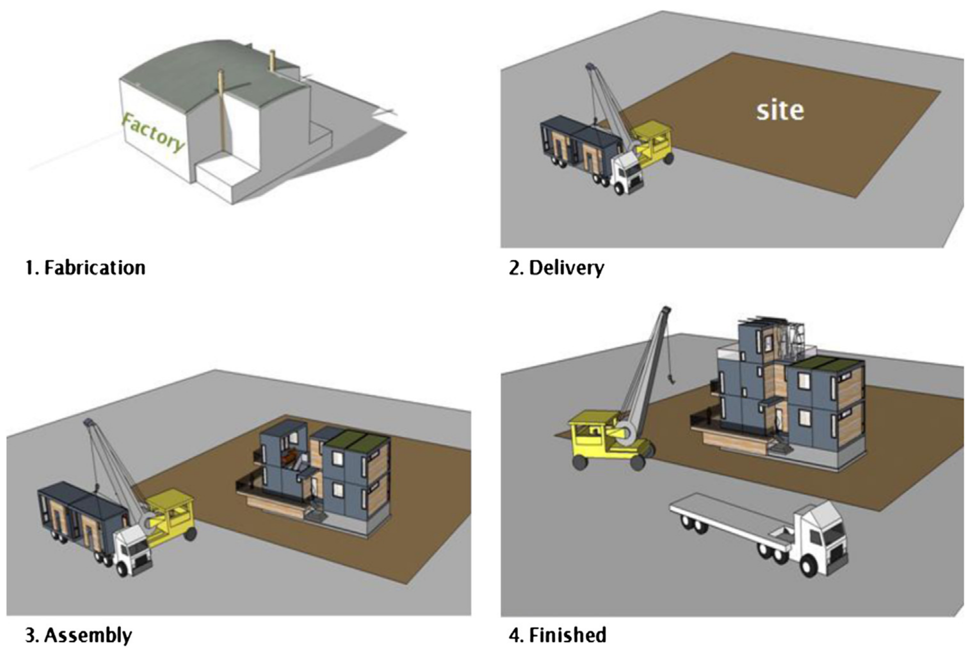

Fig. 2. General construction process for modular construction method.

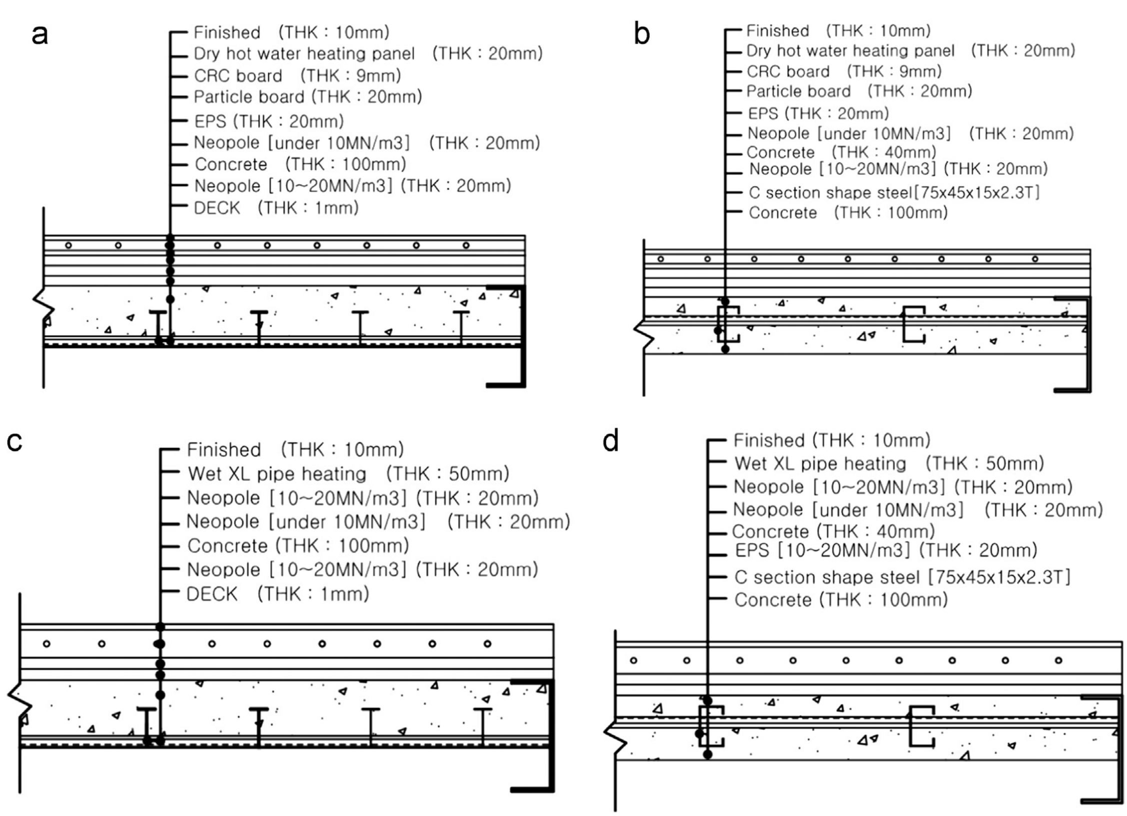

Fig. 3. Development of floor structure. (a) Dry deck, (b) dry double slab, (c) wet deck and (d) wet double slab.

its processes are completed in a way that completed modulars are lifted on site and then assembled as shown in Fig. 2.

In Korea where apartment houses are preferred, residential performance and lifting for materials is very important in modular construction as buildings are becoming high storied ones. Especially, very important technical issue is that it should reduce floor impact sound that is critical in Korea while it lightens floor structure. Therefore, this study is intended to investigate floor structure and floor impact sound effects from modular construction method whose weight is more reduced than Typical construction.

3. Research methods

The study method will be to develop lightweight flooring that meets the Korean National Housing Act and that sufficiently meets weight impact sound reduction criteria, and to conduct simulation evaluation using ANSYS and SYSNOISE.

Based on the findings from the simulation, a mock-up experiment was done to validate the acoustic characteristics and performance of the developed flooring.

3.1. Configuration of floor structure

As mentioned in research background, there isn′t any case using modular construction method which is forced to comply with House Acts. Because of this, since there is no other option but newly configuring floor structure to satisfy criterion for floor impact sound in modular construction method which are specified by House Act, this study used slabs to secure structural stability depending on loads under use. The thickness of slab is set to be 100 mm considering slope for fireproof and use of water. Resilient material on slab is EPS while it uses different modulus of elasticity of EPS expecting reduction of floor impact sound.

In addition, heating method in this method include both wet and dry type. Final configuration is shown in Fig. 3

3.2. Evaluation of simulation

This study conducted vibration analysis for floor plate using Ansys and radiated noise using Sysnoise in order to predict vibration transferring characteristics for each structure and radiated noise suggested by mock-up test.

It conducted a survey on the floor-plate modular characteristics and vibration in time of entering the load by analyzing the behavior characteristics of floor plate when the harmonic load of 1–360 Hz was added in time of analyzing the floor structure vibration by using Ansys. Radiated noise is predicted in a way that sets boundary conditions for noise analysis model based on vibration analysis results for floor plate in BEM (SYSNOISE) by importing geometry information and vibration analysis results for FEM model (ANSYS) and performs modeling for noise collection points.

3.3. Filed measurements using mock-up

This study configured mock-up using 4 structures which are developed to evaluate floor impact sound insulation performance. It produced 4 unit modules (6 m × 3 m × 2.4 m) as shown in Fig. 4b and then laminated them and evaluated floor impact sound. This floor impact sound test is carried out complying with KS F 2810-1 and KS F 2810-2 specified by KS (Korea Standard).

Bang machine (Satsuki) and impact ball (RION) are used for heavyweight impact source. Tapping machine (RION) is used for lightweight impact source. Microphone (Type 40AE, G.R.A.S) and Microphone Pre-amplifier (Type 26 CA, G.R.A.S) are used to receive sound. Received sound data is analyzed using Frequency analyzer (SA-01, RION).

4. Simulation analysis

4.1. Analysis conditions and method

This study conducted the vibration analysis of floor plate with Ansys in order to investigate the vibration transfer characteristics by structure in multi-layer floor structure used for the unit modular construction.

This study used a finite element analysis under the assumption that the floor plate is held simply on steel frame and analyzed the

Table 1
The components of a floor structure.

Material	Density (K)	Modulus of elasticity	Poisson′s ratio
Concrete	2400	27 GPa	0.25
Water heating panel	1200	1.0 GPa	0.4
Steel deck	7800	205 GPa	0.3
CRC board	1400	3 GPa	0.35
Rock wool	100	0.4 MPa	
EPS	15	3.9 MPa	
Resilience material	1100	1 GPa	0.4

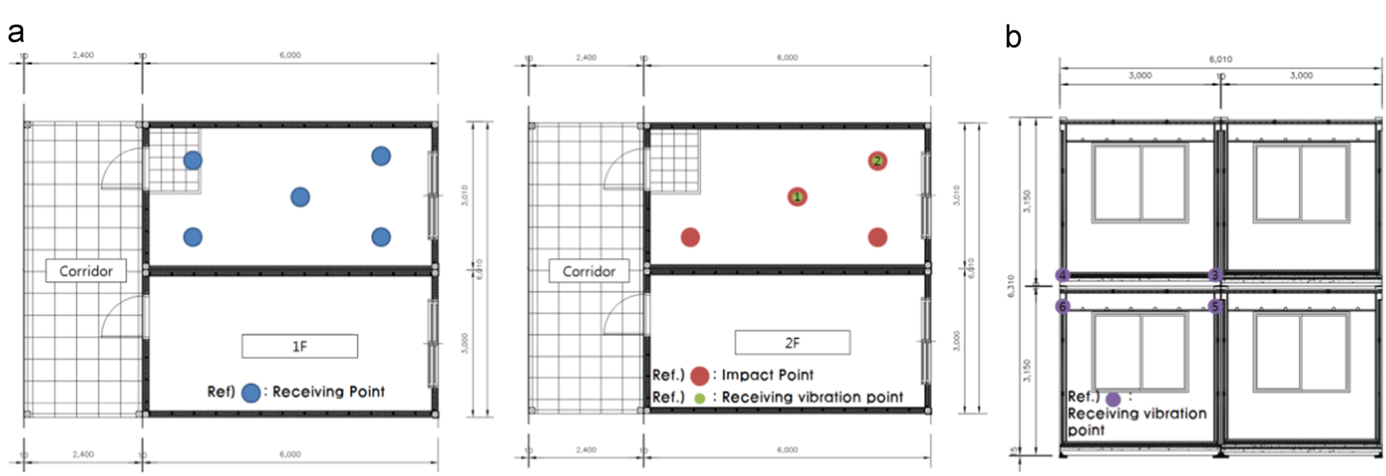

Fig. 4. Plan and section of mock-up and measuring position. (a) Mock-up plane and sound receiving points and locations for receiving vibration and (b) cross section for Mock-upand locations for receiving vibration.

considered floor structure through a harmonic analysis on the entire harmonic load.

The multi-layer floor plate was modeled by using the multi-layer shell element and the floor plate was analyzed under the assumption of simply-holding condition. Each layer is assumed to have a full-connection shape and to be accumulated in the same direction. The properties of each entered layer ware used as the above-mentioned data.

The harmonic analysis was used in the dynamic analysis and this study set that the harmonic load of 20 N this study vibrated the central part of floor plate [34]. And the vibration response was calculated at each point. This study conducted the analysis by setting 2–360 Hz, or the octave band of 250 Hz, as the band of interested frequencies 2 Hz was set as an interval of frequency.

Because the added-vibration condition is most vulnerable in the bended vibration of low mode related to inter-layer sound, the vibration was added to the central part of floor plate as the a point for evaluation used most for the measurement and evaluation of inter-layer sound.

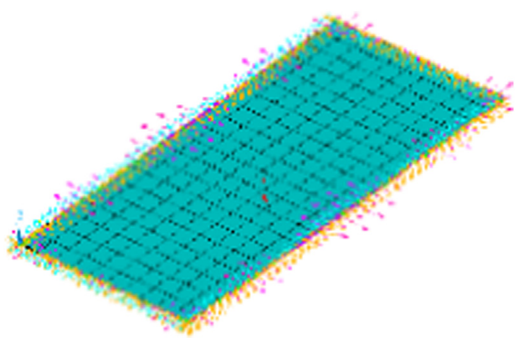

Fig. 5. The floor plate modeling in the finite element analysis, (boundary conditions and loading position).

The harmonic load of 20 N, or the average impact power of 1–500 Hz produced when an adult man walks wearing shoes on, was set as a vibration-added condition.

The vibration-absorption points were set at 2 ones away by 1 m at width and length respectively and then a central point and edge point on the ceiling plane linked to the bottom of floor plate were evaluated.

The evaluation of radiated noise is conducted by Sysnoise of LMS Corporation.

This study conducted modal characteristics for floor plate through behavioral characteristics analysis for floor plate when harmonic load of 1–360 Hz is imposed for vibration analysis using Ansys and also conducted vibration reaction survey when load is given. In addition, this study analyzed results of radiated noise analysis for each frequency band width for floor plate using Sysnoise and also predicted SPL Contour and surveyed radiation characteristics.

4.2. Properties of floor structures

This study determined physical properties as shown in Table 1 [45,46].

Because heat insulation and resilient materials have extremely low modulus of elasticity and density compared to other layers when they are installed within floor structures, they might be analyzed as spring materials. Especially when heat insulation and resilient materials are laminated, the two layers could be analyzed as a single spring with serial connection of the two layers, this study analyzed heat insulation and resilient material as one resilient layer. This study calculated equivalent modulus of elasticity and density and used them for analysis. In addition, this study assumed that resilient material is high elastic rubber.

4.3. Characteristics of vibration

As the results of floor impact vibration for RC Slab through Finite Element Method (FEM), major frequency ranges for floor

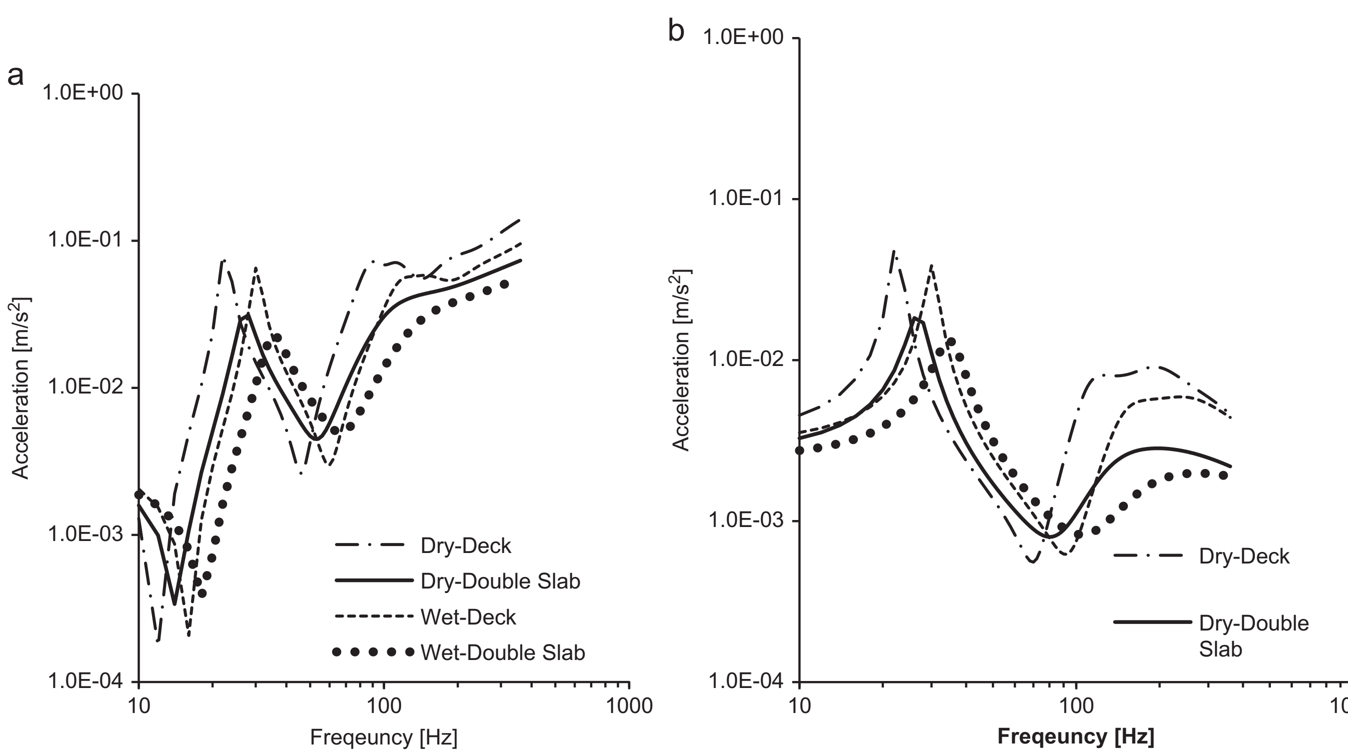

Fig. 6. Analysis result of vibration characteristics. (a) Result of vibration characteristics. At central part and (b) result of vibration characteristics. At edge part.

impact noise is less than 100 Hz whose peak frequencies are 22 Hz, 32 Hz, 44 Hz, 64 Hz, which are matched with those for vibration levels [24].

Therefore, it's verified that natural frequency for floor slab generates structural vibration sound with high energy characteristics at a certain frequency range affected by peak frequency at low frequency band width less than 100 Hz. Because of this, natural frequency and vibration mode for floor slab structures need to be considered.

Vibration characteristics of floor plate measured from central and edge of the floor is shown to be divided depending on structure the lowest floor. Edge area indicates lower acceleration value at bandwidth of more than 100 Hz than the central area. As to whether the lowest layer is made of steel deck or concrete, the steel deck structure is verified to show higher vibration level not only for resonance mode but also for overall vibration level compared with concrete deck. This study verified that natural frequency for floor structure is approximately 20–30 Hz as the result of analysis. Overall vibration reduction performance for floor plate is proved to be superior for concrete layer on the lowest floor, and the wet double floor structure whose total floor thickness is thickest is proved to show best performance.

4.4. Characteristics of impact sound levels

This study analyzed radiated noise for the floor structure using Sysnoise according to following analysis conditions. This analysis is conducted by importing structural vibration analysis results from Ansys and mesh information and noise radiated from floor plate is analyzed using boundary element method. Noise analysis is conducted for SPL distribution for each frequency range from a plane 1 m away from floor plate and radiated noise level for each frequency level. Figs. 5 and 6.

Fig. 7 shows sound pressure distribution at 31.5 Hz. Sound pressure level is shown to be higher at both ends of the plate for call cases than at the central area. This is similar to mode characteristics for this frequency bandwidth. However, a structure using finishing mortar in the bottom of finishing materials showed relative higher sound pressure level in the central area, which indicates that it is more or less different depending on dry Ondol layer and wet Ondol layer.

As shown in Fig. 8, the sound pressure at both ends is shown to be higher at 63 Hz of bandwidth similar to the case of 31.5 Hz. This could be interpreted as effects of vibration characteristics due to modal of the floor plate to 63 Hz. In addition, a structure with wet double slab is proved to show higher sound pressure level at both ends and central area compared to other structures. In addition, higher sound pressure level is measured at both ends and central area as well excepting 'Deck floor'.

As shown in Fig. 9, it indicates that the sound pressure level radiated from 'Deck floor' structure at frequency level more than 125 Hz is more concentrated on the central area compared with other structures while it is relatively low compared to both ends.

Fig. 10 shows a sound pressure level for each frequency bandwidth from each structure. In general, the sound pressure level for the wet double slab shows the lowest value as the results

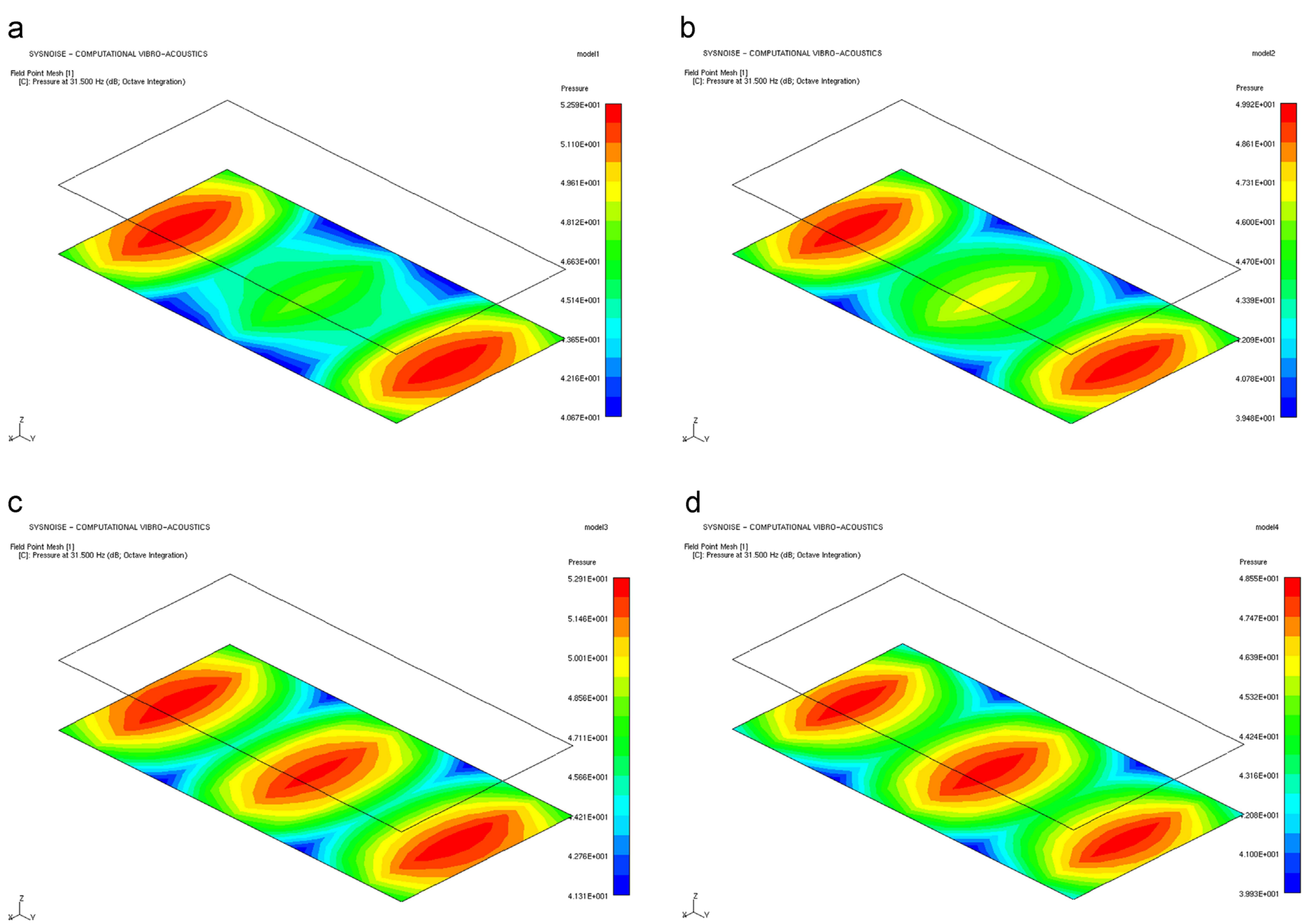

Fig. 7. Sound pressure level at 31.5 Hz. (a) Dry-deck, (b) dry-double slab (c) wet-deck and (d) wet-double slab.

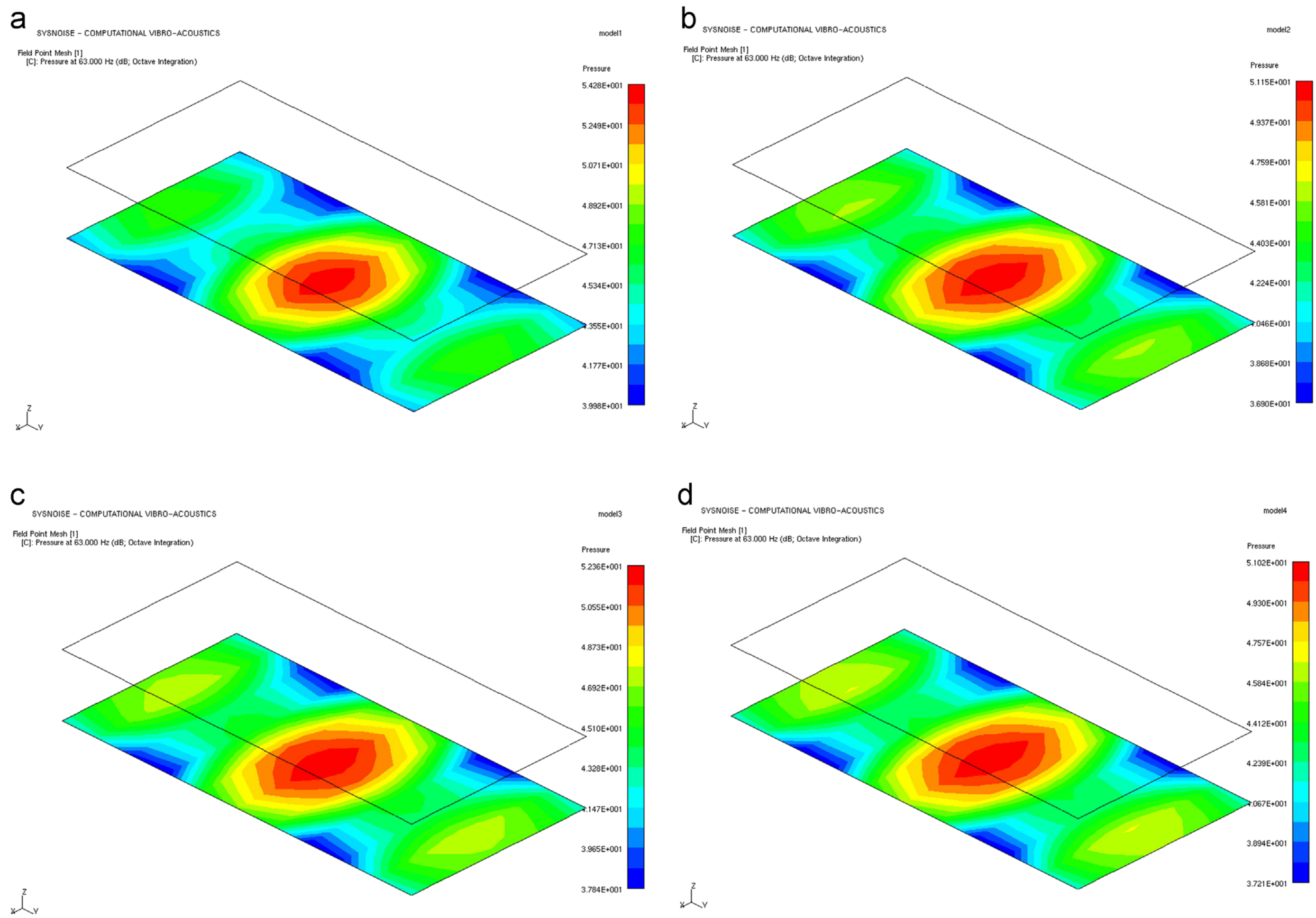

Fig. 8. Sound pressure level at 63 Hz. (a) Dry-deck, (b) dry-double slab (c) wet-deck and (d) wet-double slab.

of analysis. Between 200 Hz and 500 Hz, is lots of difference depending on each structure. The difference between the maximum and minimum value in this frequency range is shown to be approximately 10 dB.

4.5. Result of simulation analysis

First of all, in terms of structural aspects, as wet double slab has a structure with heavy concrete installed at the floor, its resonance frequency is higher than other structures However, its amplitude is for all frequency ranges except resonance frequency bandwidth. In addition, from the results of radiated sound level as well, wet double slab structure is proved to show lower sound pressure level for both central and edge areas compared to other structures. Especially, the sound pressure level at high frequency bandwidth at edge is verified to more than 10 dB lower than other structures. Analysis of the sound pressure level of 31.5 Hz and 63 Hz showed significant differences in dry and wet construction structures.

Therefore, wet double slab whose heavy concrete pushes floor structure is proved to show better vibration reduction and radiated noise reduction performance compared with other structures.

5. Field measurements using mock-up

5.1. Standard of floor impact sound in Korea

Korea generally prefers apartment houses. Therefore, Korean House Acts is well satisfying residential performance. Especially House Acts specify performance criteria for building itself on mandatory basis especially against floor impact sounds.

The standard of floor impact sound includes the lightweight and the heavyweight impact sound as Table 2. The lightweight impact sound is required to be less than 58 dB and the heavyweight impact sound to secure the performance less than 50 dB. The modular housing has a problem to reduce the load of floor plate and to secure the floor impact sound insulation performance. The problem should be solved in order the modular housing to be applied to the domestic apartments. Currently, Korea uses Bang machine to evaluate heavyweight impact sound, which is weight standard impact sound source. However, as Rubber Ball specified by ISO standard [47,48] is included in Korean standard [49], a performance standard for rubber ball will be prepared. It is expected that minimum standard is 50 dB for Bang machine and 47 dB for Rubber Ball

5.2. Characteristics of vibration on mock-up

Fig. 11 shows the results of receiving vibration at the center and edge of floor panel in mock-up which is created by a standard heavyweight impact source, bang machine. Vibration characteristics measured at center and edge of the floor is proved to be dependent of structure in the bottom floor. Edge area showed lower vibration acceleration level in more than 30 Hz of bandwidth than the central area. Deck type structure is proved to have higher vibration level including resonance in floor. Resonance mode, similar to simulation, is listed by the order of dry deck, dry double floor structure, wet deck and wet double floor structure (dry deck showed the highest resonance) The peak of resonance is lowered at the descending order

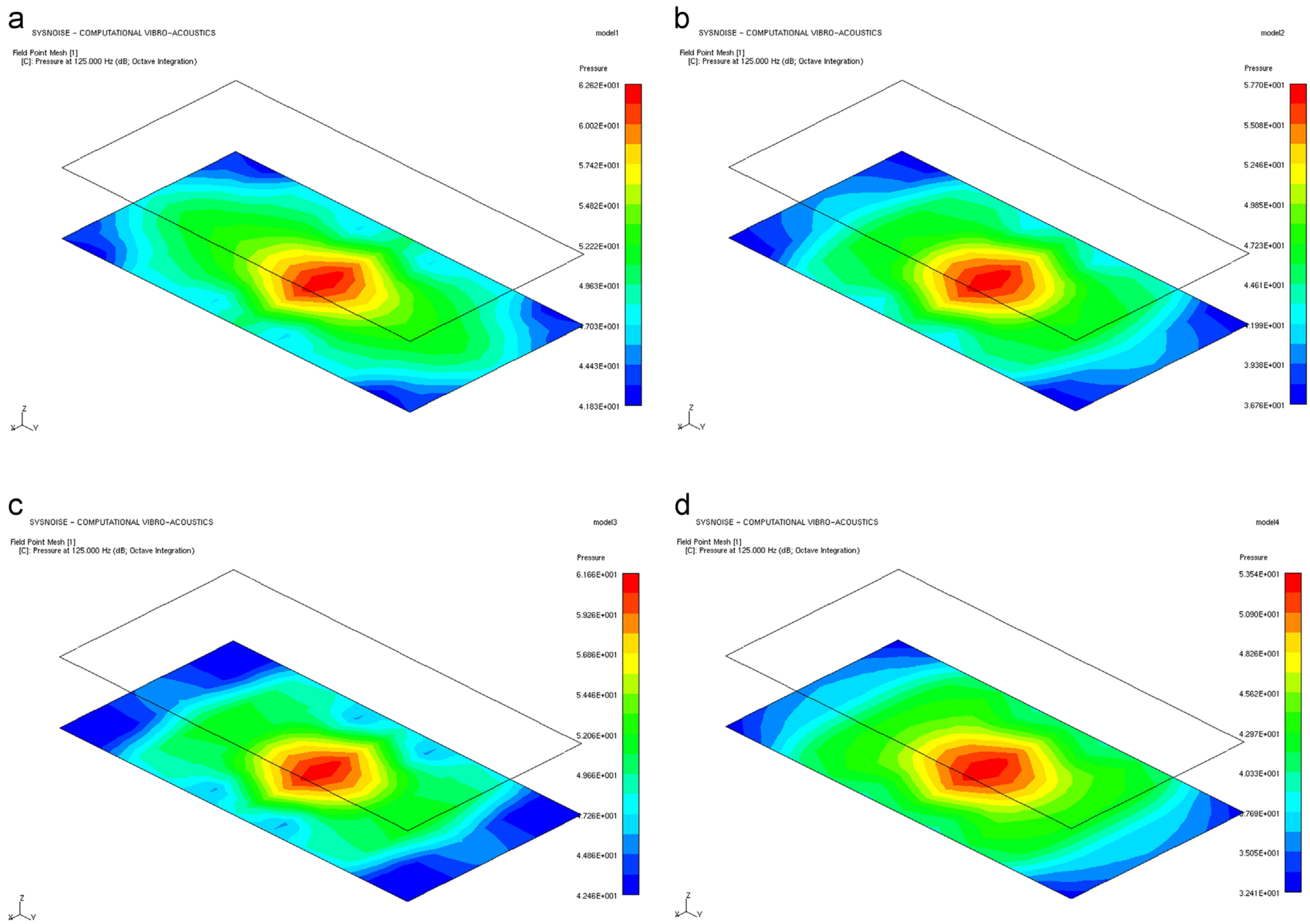

Fig. 9. Sound pressure level at 125 Hz. (a) Dry-deck, (b) dry-double slab (c) wet-deck and (d) wet-double slab.

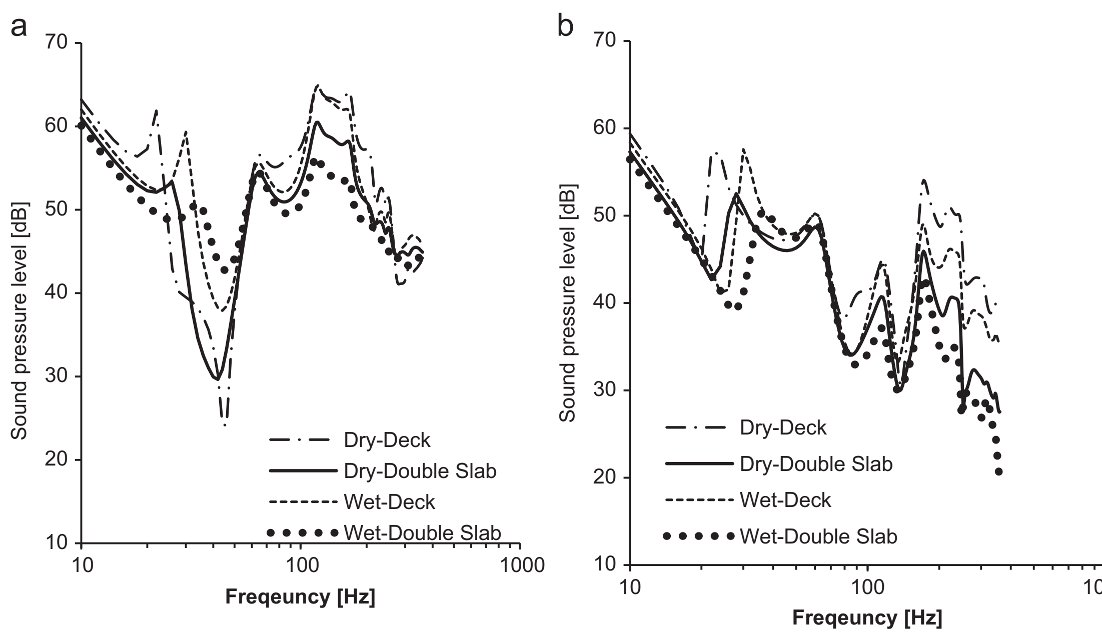

Fig. 10. Sound pressure level of floor structure. (a) Sound pressure level of floor structure at Central part and (b) sound pressure level of floor structure at Edge part.

of: dry deck, wet deck and dry double floor structure and wet double floor structure. Natural frequency for the floor structure to be measured is approximately 30 Hz. This is similar to the result of simulation. Vibration reduction performance for overall floor panel in concrete floor type is affected to be better than deck type, and wet heating type of floor which is finished with driven mortar is shown

to give excellent vibration reduction than wet heating type of floor structure.

5.3. Characteristics of floor impact sounds on mock-up

Fig. 12 shows analysis from heavy impact sound measurement result for 4 structures by bang machine and ball. Dry type in Fig. 3 showed low impact sound level by ball at whole frequency ranges. Wet type showed higher ball measurement result at 100 Hz to 400 Hz than bang machine. Wet type, which casted mortar on Ondol (Korean heating system), indicated higher impact sound level by all at certain frequency ranges compared with Dry type.

Double floor structure also showed same frequency characteristics as deck type. Dry type showed lower impact sound level than bang machine. Wet type showed higher impact sound level at certain frequency level than bang machine. More increase of floor impact sound level at 800 Hz in wet double floor structure than bang machine is believed to be caused by the effects of background noise.

Difference in impact sound between bang machine and ball is believed to be caused by characteristics of impact force in impact source and wet type shows higher impact absorption by ball than bang machine. From the result of bang machine measurement, a structure applying wet type showed lower floor impact sound level at more than 80 Hz than dry type. For larger reduction of impact force from bang machine, wet type is believed to be more effective than ball. All measurement structures generated resonance at approximately 30 Hz as shown vibration measurement result, which is believed to increase sound pressure level.

Ball measurement result showed lower impact sound level at 63 Hz than bang machine. It clearly showed higher value at 125 Hz and 250 Hz. Resonance by resilient material is proved to be shown at 63 Hz when vibration is created on floor by bang machine. Deck type showed lower impact sound level deviation between bang machine and ball at 63 Hz than double floor structure.

Measurement result is shown as single evaluation value using reverse A-curve in Table 3. As a result of analysis, all floor structures excepting dry deck are proved to satisfy legal standard (50 dB) of bang machine. Especially wet double floor structure showed best performance among 4 structures.

Fig. 13 shows measurement result for lightweight impact sound indicating that dry type gives better performance than wet type.

The four structures all showed similar impact sound patterns with the peak value at 160 Hz, and a decreasing pattern with increasing frequency.

As impact force from lightweight impact source is not much strong and much affected by surface finishing material, dry type with better insulation performance is believed to block vibration more effectively than wet type. Unlike for heavyweight impact source, lightweight impact sources are affected more by the material property of the final surface material because it produces less impact, which is what may have produced the results. The ability to block lightweight impact sound was greater for dry board types compared to mortar types.

5.4. Comparison with floor impact sound of RC (wall type structure)

Fig. 14 shows a measurement result of heavyweight impact sound in the floor structure applying 6 kinds of resilient materials applied to box frame buildings [50]. The floor structure is composed of slab, resilient materials (20–30 mm) and lightweight aerated concrete of 40 mm and mortar of 40 mm. Compared to a result of bang machine, the measurement result by using a ball showed the lower impact sound level in 63 Hz. It's identified that the excessive impact force of bang machine (4200 N) amplified the impact sound level and then produced the difference of 10 dB. To compare the result of Fig. 14 to that of this study in Fig. 12, it was found that the impact sound level is amplified equally in 63 Hz by using the bang machine and likewise, the impact sound level of ball was shown higher in 125 Hz and 250 Hz than that of bang machine.

Most of domestic apartment houses are constructed with box frame. Although standard floor structure or certified floor structures applying current resilient materials are used for box frame floor, what both structure have in common is to use resilient material. Although various materials and shapes are sued as resilient materials, they tend to generate a problem that amplifies heavyweight impact sound at 63 Hz of bandwidth due to installation of upper Ondol layer on

Table 2
Light and heavyweight floor impact sound insulation performance grade standard.

Grade	Lightweight impact sound [Reversed A-weighted normalized floor impact sound pressure level ($L'_{n,AW}$)]	Heavyweight impact sound [Reversed A-weighted floor impact sound pressure level ($L'_{i,Fmax,AW}$)]
1	$L'_{n,AW} \leq 43$ dB	$L'_{i,Fmax,AW} \leq 40$ dB
2	$43 \text{ dB} < L'_{n,AW} \leq 48$ dB	$40 \text{ dB} < L'_{i,Fmax,AW} \leq 43$ dB
3	$48 \text{ dB} < L'_{n,AW} \leq 53$ dB	$43 \text{ dB} < L'_{i,Fmax,AW} \leq 47$ dB
4	$53 \text{ dB} < L'_{n,AW} \leq 58$ dB	$47 \text{ dB} < L'_{i,Fmax,AW} \leq 50$ dB

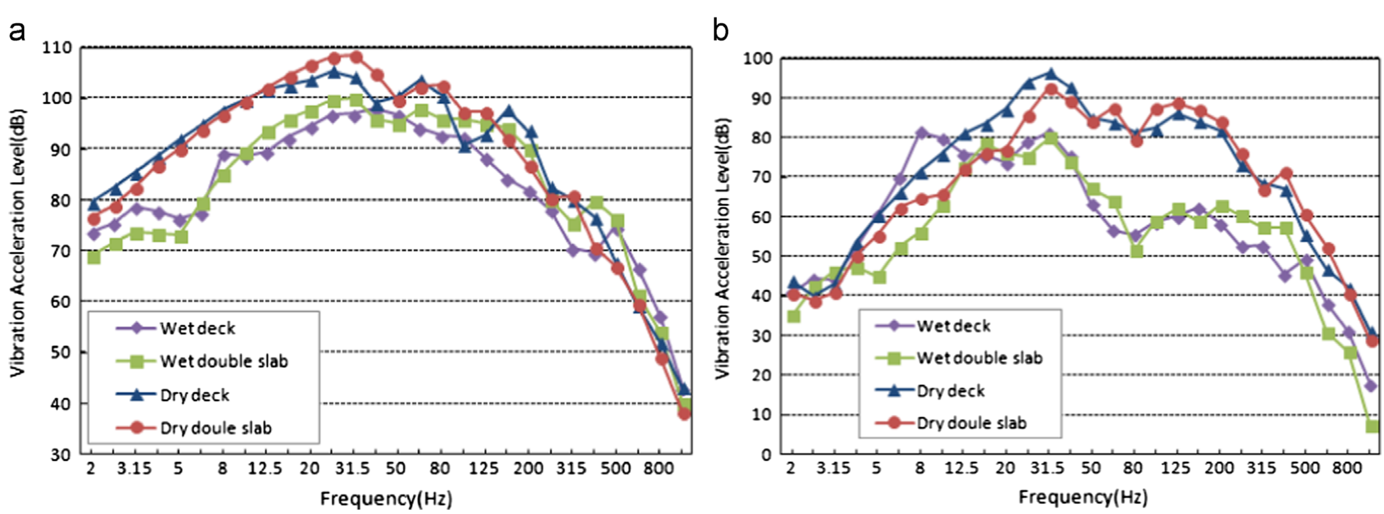

Fig. 11. Analysis result of vibration characteristics. (a) Central part vibration recoding and (b) edge part vibration recording.

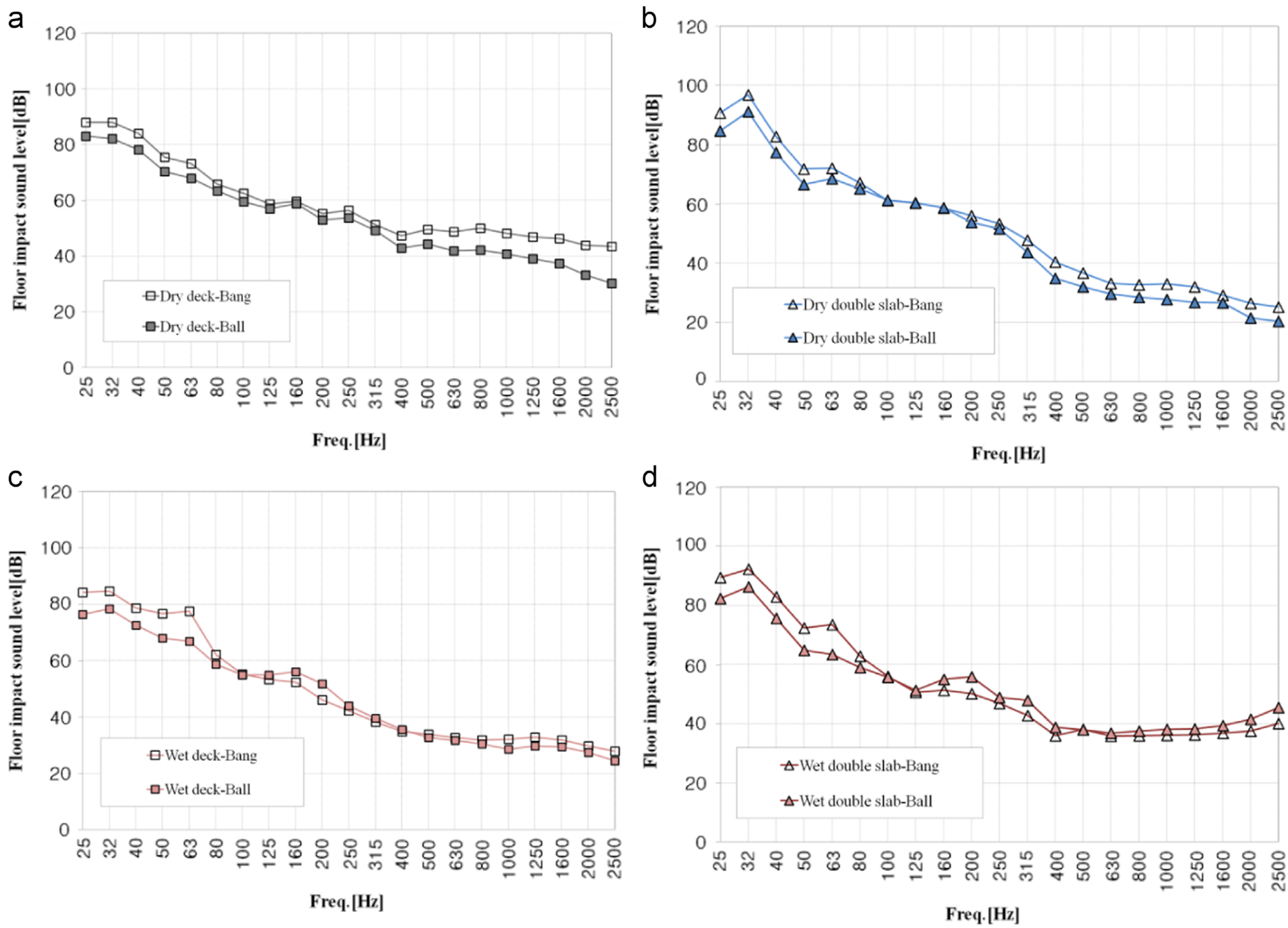

Fig. 12. Test results of heavyweight floor impact sound (1/3 Octave). (a) Dry deck, (b) dry double slab, (c) wet deck and (d) wet double slab.

Table 3
Floor impact sound level (1/1 Octave).

Type	63 Hz	125 Hz	250 Hz	500 Hz	A-Weight	Impact source
Dry deck	77.8	65.5	59.6	53.4	52	Bang machine
	72.9	63.4	57.2	48.0	48	Impact ball
Dry double floor	75.6	65.0	58.3	42.5	50	Bang machine
	71.8	65.0	56.1	37.5	48	Impact ball
Wet deck	80.2	58.6	48.1	38.6	50	Bang machine
	70.7	60.1	52.7	38.4	45	Impact ball
Wet double floor	76.3	58.1	52.4	41.5	46	Bang machine
	67.8	59.2	57.3	42.8	45	Impact ball

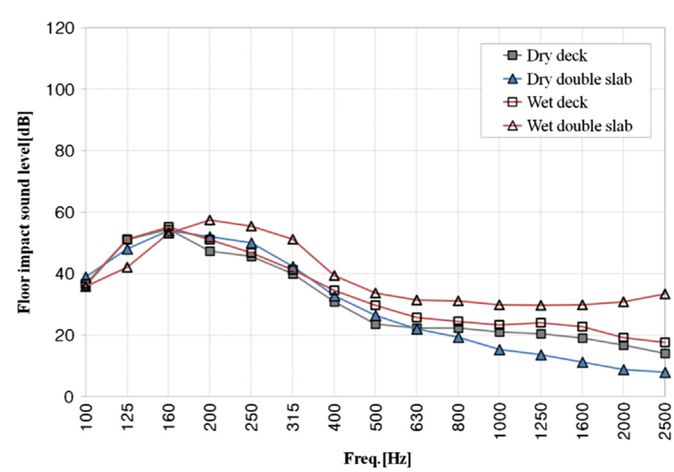

Fig. 13. Test results of lightweight floor impact sound.

resilient material. From this phenomenon, as shown from the measurement result on floor structure applying different resilient material in Fig. 15, measurement result by bang machine shows higher level than that of ball whose impact force exposure level is low at 63 Hz. Impact sound level of ball indicates higher level at 125 Hz and 250 Hz than bang machine. Although difference in impact sound level at 63 Hz of bandwidth between bang machine and ball indicates similar pattern as wet construction method in modular structure, the level is shown to be higher in box frame structure than wet construction method. For reduction effect of 250 Hz, box frame structure indicates higher level than modular structure. Even from overall measurement result graph, the slope for impact sound level graph in box frame structure is proved to be steeper than modular structure. Box frame structure is proved to increase reduction effect for heavyweight impact sound as bandwidth is shifting to high frequency area.

5.5. Comparison with floor impact sound of wooden structure

This study compared wooden structure with modular structure referring to measurement result of Japan. Fig. 16 shows 30 measurement results of heavy weight impact sound from Japanese

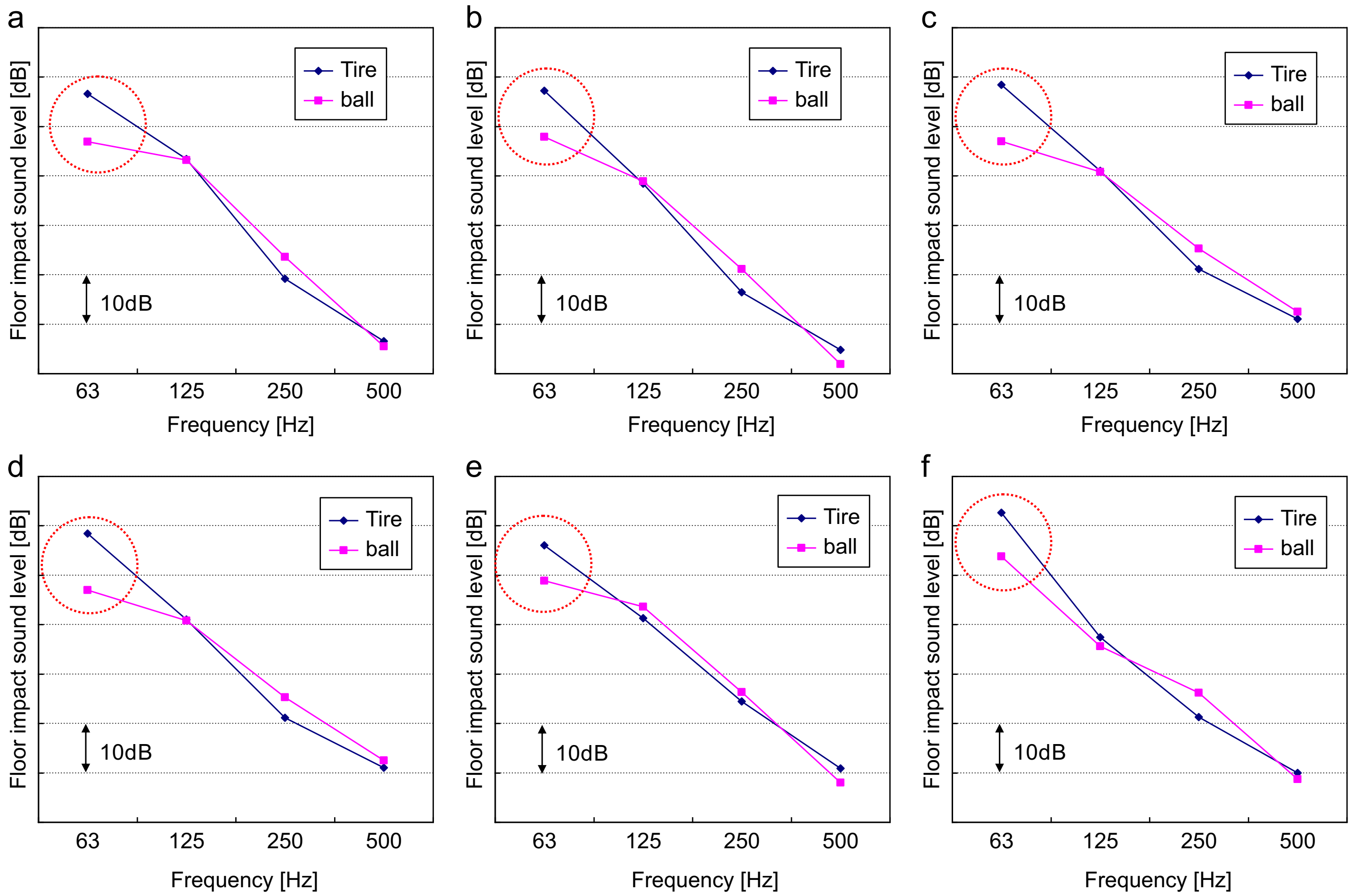

Fig. 14. Test results comparison of a bang machine and a ball. (a) No.1, (b) No.2, (c) No.3, (d) No.4, (e) No.5 and (f) No.6.

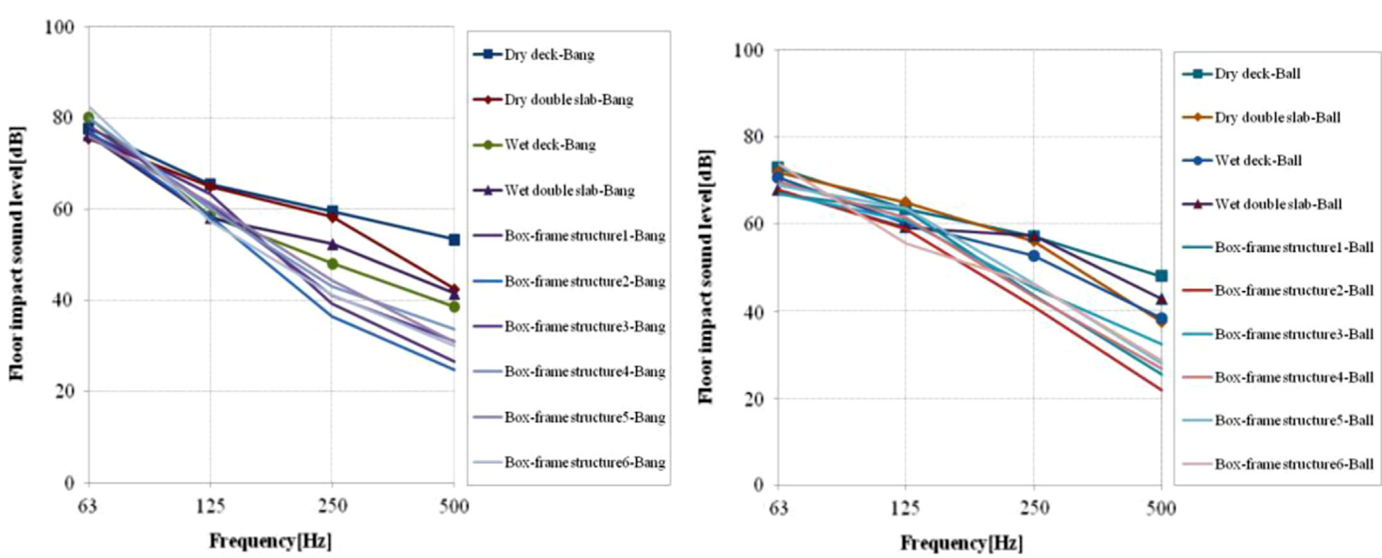

Fig. 15. Comparisons between modular construction and Reinforced construction of heavyweight floor impact sound.

wooden structure and it indicates a general trend which impact sound level at 63 Hz is low and it becomes lowered as frequency is increasing. Measurement result from ball showed lower level at 63 Hz than from bang machine and ball impact sound level showed increase at more than 125 Hz of frequency.

Difference of wooden structure in sound level between 63 Hz and 125 Hz is shown to be approximately 20 dB, which is believed to be similar to those of wet construction method and wall type structure from modular structure. The sound level is proved to show 10 dB of difference between neighboring bandwidths at more than 125 Hz of bandwidth, which in turn is believed to be more similar to modular structure rather than wall type structure.

However, impact sound level (bang machine) at 63 Hz is 90–105 dB, which indicates higher sound level than general wall type.

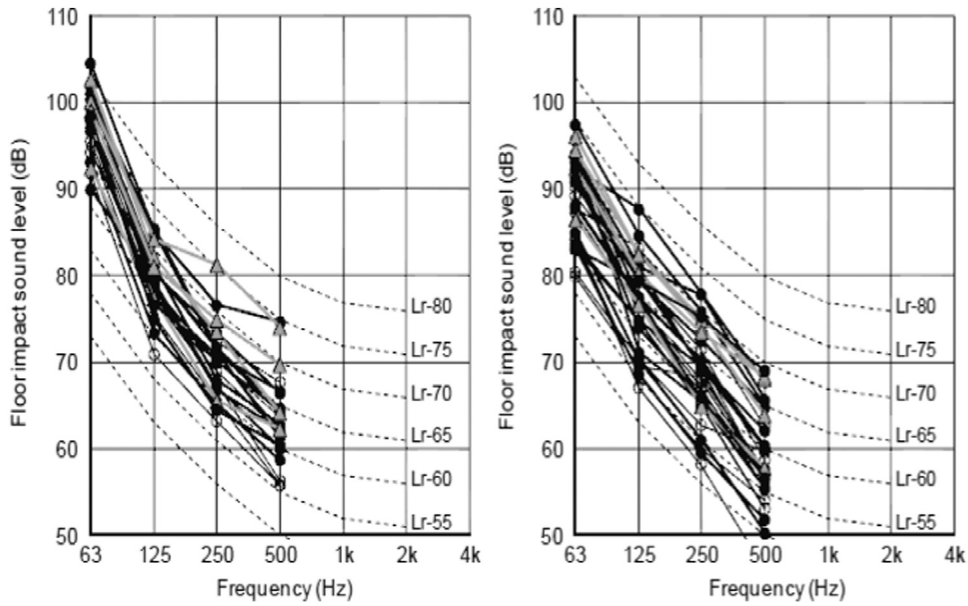

Fig. 16. Comparisons between modular construction and wooden structure of floor impact sound.

6. Conclusion and discussion

This study purpose that floor structures to apply modular structure among prefabricated construction which are suggested as new construction method to solve problems related to lack of human resources in construction sites and to enhance quality.

Evaluation of the ability to reduce noise vibration of the four different flooring structures showed that the flooring with double concrete slabs had the highest performance in reducing heavy-weight impact sounds. It was also found that the use of mortar for insulation also increased the vibration reduction effect. Heavy-weight impact sound was affected significantly by the load on the flooring structure, whereas for lightweight impact sound the performance was higher with dry construction insulation structures compared to wet construction structures. Lightweight impact sound is caused by less impact on the floor, which may be why dry insulation construction had better ability to absorb smaller vibrations.

For next research, we will continue to develop lightweight floor structure to save cost for thickness while it secures performance of heavyweight impact sound performance meeting requirements of modular houses.

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References

[1] World Commission on Environment and Development (WCED), Our common future (The bruntland report). Oxford University Press; 1987. p. 43.
[2] The UK Government Sustainable Development Strategy, Securing the future—delivering UK sustainable development strategy, Presented to Parliament by the Secretary of State for Environment, Food and Rural Affairs; 2005.
[3] Burgan Bassam A, Sanso Michael R. Sustainable steel construction. Journal of Constructional Steel Research 2006:1178–82.
[4] Xing WH, Fraaij A, Pietersen H, Rem P, Van Dijk K. The quality improvement of stony construction and demolition waste (CDW). Journal of Wuhan University of Technology, Materials Science Edition 200478–85.
[5] Li Yashuai, Zhang Xueqing. Web-based construction waste estimation system for building construction projects. Automation in Construction 2013.
[6] Meyer C. The greening of the concrete industry. Cement and Concrete Composites 2009:601–5.
[7] Waste DM. Characterization Study, Department of Environment, City of Chicago. Illinois, United States; 2010.
[8] Tam VWY, Gao XF, Tam CM, Chan CH. New approach in measuring water absorption of recycled aggregates. Construction and Building Materials 2008 (364–349).
[9] Wong SHL, Tam WCK, Yim AHL, Ip NHY. Monitoring of solid waste in Hong Kong: Waste Statistics for 2005. Hong Kong, China: Environmental Protection Department; 2006.
[10] Ulsen C, Kahn H, Hawlitschek G, Masini EA, Angulo SC, John VM. Production of recycled s and from construction and demolition waste. Construction and Buildings Materials 2013:1168–73.
[11] Burgan Bassam A, Sanso Michael R. Sustainable steel construction. Journal of Constructional Steel Research 2006:1178–82.
[12] Re-thinking construction, The report of the construction task force (The Egan Report), the Office of the Deputy Prime Minister, UK; 1998.
[13] Lawson RM, Ogden RG. 'Hybrid' light steel panel and modular systems. Thin Walled Structures 2008:720–30.
[14] Jeon Jin Yong, Ryu Jong Kwan, Jeong Jeong Ho, Tachibana Hidek. Review of the impact ball in evaluating floor impact sound. Acta Acustica united with Acustica 2006:777–86.
[15] Neves e Sousa A, Gibbs BM. Low frequency impact sound transmission in dwellings through homogeneous concrete floors and floating floors. Applied Acoustics 2011:177–89.
[16] Johansson Carin. Low-frequency impact sound insulation of a light weight wooden joist floor. Applied Acoustics 1995:133–47.
[17] Jeon, Jin yong, Young Jeong, Song, Hee-Soo, Kim, Min-Bae, Lee, Young Je. Noise and vibration characteristics of heavy-weight floor impact by using damping materials. In: Proceedings of the Korean Society for noise and vibration engineering conference; 2004. pp. 97–102.
[18] Jeong, Jeong Ho; Yoo, Seung Yup; Jeon, Jin Yong. The effect of a reinforcement slab and beam on heavy-weight impact sound. In: INTER-NOISE and NOISE-CON congress and conference proceedings. Institute of Noise Control Engineering; 2005. pp. 1226–1231.
[19] Kim Kyoung woo, Ghoi Gyoung Seok, Choi Hyun Jung, Yang Kwan Seop. Evaluation of floor impact sound performance according to the reduction methods. Transactions of the Korean Society for Noise and Vibration Engineering 2004:131–6.
[20] Jeong Ho Jeong, Young Jeong, Song, Hee-Soo, Song, Hee Soo, Jeon, Jin yong. Investigation of floor sound levels in Rahmen structure multi-story residential buildings. In: Proceedings of the Korean Society for noise and vibration engineering conference; 2004. pp. 269–274.
[21] Jeong, Jeong Ho, Seung Yup Yoo, Jin Yong Jeon. The effect of a reinforcement slab and beam on heavy-weight impact sound. In: INTER-NOISE and NOISE-CON congress and conference proceedings, Institute of Noise Control Engineering; 2005. pp. 1226–1231.
[22] Lee Won-Hak, Haan Chan-Hoon. Improvement of the floor impact noise of concrete slab using SBR Latex-modified mortar. Architectural Institute of Korea 2010;26(04):79–87.
[23] Young Jeong, Song, Hee-Soo, Jeon, Jin yong, Kim, Jin Soo. Heavy-weight floor impact sound characteristics of standard laboratory by slab thickness. In:

Proceedings of the Korean Society for noise and vibration engineering conference; 2004. pp. 103–108.
[24] Seo Sang Ho, Jeon Jin yong. 2-Dimensional floor impact vibration analysis in bare reinforced concrete slab using finite element method. Transactions of the Korean Society for Noise and Vibration Engineering 2005:604–11.
[25] Birgit Rasmussen Jens Holger Rindel. Sound insulation between dwellings—descriptors applied in building regulations in Europe. Applied Acoustics 2010:171–80.
[26] Warnock CC. Floor research at NRC Canada. In: Conference in building acoustics acoustic performance of medium-rise timber buildings; 1998.
[27] Warnock CC. Impact sound ratings: ASTM versus ISO, InterNoise 2004; 2004. ID 694.
[28] SP Report 2008, acoustics in wooden buildings—state of the art; 2008.
[29] Vinnova Project 2007-01653, SP Technical Research Institute of Sweden; 2008.
[30] Blazier WE, DuPree RB. Investigation of low-frequency footfall noise in wood-frame, multifamily building construction. Journal of the Acoustical Society of America 1994:1521–32.
[31] Bodlund K. Rating of impact sound insulation between dwellings, technical report SP-RAPP 1985-01. Includes the paper: Alternative reference curves for evaluation of the impact sound insulation between dwellings. Journal of Sound and Vibration 1985:381–402.
[32] Hagberg K. Evaluation of sound insulation in the field. Licentiate thesis. Lund University, report TVBA 3127; 2005.
[33] Lee Seong-Soo. A prediction equation for natural frequency of reinforced concrete floor systems, doctoral dissertation. Yonsei University; 2000.
[34] Kim Kyoung-Woo, Jeong Gab-Cheol, Yang Kwan-Seop, Sohn Jang-yeul. Correlation between dynamic stiffness of resilient materials and heavyweight impact sound reduction level. Building and Environment 2009;44(8):1589–600.
[35] Hong Sung-Gul, Cho Bong-Ho, Chung Kyung-Soo, Moon Ju-hyuk. Behavior of framed modular building system with double skin steel panels. Journal of Constructional Steel Research 2011;67(6):936–46.
[36] Roberts Clifford R, Britz William E. - Modular Buildings. Planning and Designing Research Animal Facilities 2009:173–8.
[37] Modular Building Institute, Commercial modular construction report, Modular Building Institute; 2008. pp. 1–23.
[38] Han Sang Hyeok, Al-Hussein Mohamed, Al-Jibouri Saad, Yu Haitao. Automated post-simulation visualization of modular building production assembly line. Automation in Construction 2012;21:229–36.
[39] Haitao Yu, Tarry, Mohamed, Reza, Tarry Tweed, Mohamed Al-Hussein, Reza Nasseri, Development of lean model for house construction using value stream mapping, Journal of Construction Engineering and Management, ASCE 135 (8), 2009:782–790.
[40] Roberto J. Arbulu, Iris D. Tommelein., Value stream analysis of construction supply chains: case study on pipe supports used in power plants. In: plants Proceedings of tenth annual conference of Tenth Annual Conference of the international group for lean construction, IGLC-10, Gramada, Brazil; 2002. 183–195.
[41] Wang Ping Mohamed, Yasser Simaan M, Abourizk RTony Rawa. Flow production of pipe spool fabrication: simulation to support implementation of lean technique. Journal of Construction Engineering and Management, ASCE 2009;135(10):1027–38.
[42] Ayman Abu Hammad. A decision support system for manufactured housing production process planning and facility layout. PhD thesis. Dept of Civil and Environmental Engineering, University of Cincinnati; 2003.
[43] Abu Hammad Ayman, Senghore O, Makarand Hastak, Matt Syal. Simulation model for manufactured housing processes. Journal of Computing in Civil Engineering, ASCE 2004;22(3):286–97.
[44] Abhi Sabharwal. Manufactured housing components assembly redesign process and its impact on production process and facility layout. MS thesis. Construction Management Program, Michigan State University, USA; 2004.
[45] Cremer L, Heckl M, Petersson BAT. Structure-boarne sound. 3rd ed. Germany: Springer; 2005.
[46] Tor Erik Vigran, Building acoustics, 2008, Taylor & Francis; New York.
[47] Ayman Abu Hammad. A decision support system for manufactured housing production process planning and facility layout. PhD thesis. Dept of Civil and Environmental Engineering, University of Cincinnati; 2003.
[48] Abu Hammad Ayman, Senghore O, Makarand Hastak, Matt Syal. Simulation model for manufactured housing processes. Journal of Computing in Civil Engineering, ASCE 2004;22(3):286–97.
[49] Korean Standard, KS F 2810-2, Field measurement of impact sound insulation of floors—Part 2: floors-Part2: Method using standard heavy impact source; 2012.
[50] Kwan-Seop Yang, Kyoung-Woo Kim and Hyun-Jung Choi, Current state of approval floor structure and impact sound insulation performance in laboratory, Proceedings of Inter-noise 2010, 2010.